Mitigation of Environmental Impacts of Derelict Fishing Gear Through Debris Removal and Environmental Monitoring

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Background

Prior to the 1950s, discarded or lost fishing gear posed little long-term environmental threat, as nets were almost exclusively composed of natural fibers (linen, cotton, jute, hemp, manila and sisal) susceptible to environmental degradation (Uchida 1985). Nylon webbing first appeared in Japanese nets in 1949, and by 1964, 95% of nets produced in Japan were composed of synthetic fibers (Japan Chemical Fibers Association 1971). Currently, almost all of the fishing gear in developed countries is composed of durable synthetic fibers (Klust 1973). The production and availability of synthetic fibers, coupled with mechanization and echo sounding, revolutionized the fishing industry (Kristjonsson 1959) by producing nets that were functionally impervious to degradation (Andrady 1990). The durability of fishing gear composed of synthetic fibers, when discarded or lost, generates persistent waste in the marine or littoral environment.

Fishing gear loss appears to be increasing as a result of economic pressures that have contributed to modifications in fishing operations and efforts in a wide variety of fisheries (Carr and Harris 1997). Carr and Harris (1997) link dwindling target stocks, advances in equipment handling and materials technology, solid waste disposal limitations and loss reimbursement programs to increased potential for fishing gear loss or discard. Estimates of gear loss have primarily been inferred based on fishery effort, limited fishery observer data or beach surveys, with much emphasis on the Pacific region. Uchida (1985) reported that in the mid 1980s, 170,000 km of gill net, 2,000 km of purse seine, 5,500 km of trawl net and 8,900 km of miscellaneous net gear were available to North Pacific net fisheries and provided this as an estimate of the size of the source from which derelict fishing gear was generated. Uchida (1985) speculated that gear losses were highest in the gill net fisheries, followed by trawl fisheries and set net fisheries. Low *et al*. (1985) utilized observer data to generate minimum estimates of gear loss in Alaska trawl fisheries from 1954 to 1983, which they reported at 65 nets total. Sighting surveys conducted in the North Pacific from 1986 to 1991 identified two regions of high derelict fishing net density, 20º to 30º N, 150º to 130º W and 30º to 40º N, 140º to 150º E (Matsumura and Nasu 1997). A significant high density area of derelict fishing gear was also reported northeast of Hawaii by Mio *et al.* (1990). Kubota (1994) proposed a convergence zone associated with the North Pacific subtropical high as a mechanism for the disproportionate accumulation of marine debris from the greater North Pacific in the area north of Hawaii.

Recent oceanographic measurements support Kubota's model (see Brainard *et al.* 2000) and suggest a non-homogenous distribution of marine debris. The amount of derelict fishing gear accumulating in this region has not decreased since the early 1980s, despite the ratification of MARPOL Annex V (1973/1978)[1] by the majority of the world's fishing nations (Henderson, in review).

Derelict fishing gear, once in the marine and littoral environment, has widespread environmental and economic impacts. One hundred thirty-six species of marine animals have documented records of entanglement in marine debris, including numerous threatened and endangered species (Laist 1996). Eighty-six percent of the world's sea turtle species and 28% of the world's marine mammal species, as well as seabirds, fish and crustaceans have been recorded entangled in derelict fishing gear. Mortality resulting from entanglement in fishing gear has been proposed to explain population level declines in the northern fur seal (*Callorhinus ursinus*), a seal listed as depleted under the Marine Mammal Protection Act of 1973 (Fowler *et al*. 1990). The critically endangered Hawaiian monk seal (*Monachus schauinslandi*) suffers the greatest entanglement rate of any pinniped (seal or sea lion) reported to date, nearly twice that of the northern fur seal (Henderson, in review). Derelict fishing gear may also negatively affect target stocks, as well as noncommercial species, by continuing to fish after becoming lost or discarded, thus removing animals otherwise potentially available to active fishing operations. The greatest potential for this "ghost-fishing" is associated with gillnets, followed by trap or pot gear (Carr and Harris 1997). Derelict fishing gear may also function as a vector for the introduction of alien species. As nets circulate around ocean gyres they are subject to colonization by encrusting, epibiont or other biota and may subsequently transport these organisms to novel environments (Winston *et al.* 1997). Recently, derelict fishing gear has been identified as a direct threat to coral reef ecosystems through the abrading and scouring of coral substrate, as circulating nets snag on shallow reefs (Brainard *et al*. 2000, Donohue, unpublished data).

Here we briefly review recommendations pertaining to debris monitoring and removal from previous meetings, followed by a discussion of survey techniques used to monitor marine and littoral environments for derelict fishing gear. We also describe selected methods employed to remove derelict fishing gear from these environments. Lastly, we discuss the use of remote-sensing technology to aid in the prediction of areas where marine debris is likely to accumulate, and the potential utility of remote-sensing technology to monitor and manage ecosystem health, including marine debris burden. We hope this abridged summary will stimulate further discussion on the monitoring and removal of derelict fishing gear and direct the reader to the primary literature for additional detail.

Summary of Previous Conference Recommendations

Over the past 16 years, several international meetings have convened to address the problem of marine debris in the world's oceans. These included the Workshop on the Fate and Impact of Marine Debris (1984; Honolulu, HI), The North Pacific Rim Fishermen's Conference on Marine Debris (1987; Kailua-Kona, Hawaii), The Second International Conference on Marine Debris

[1]Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, London, 1978. 17.I.L.M. 546.

(1989; Honolulu, Hawaii) and The Third International Conference on Marine Debris (1994; Miami, Florida). In addition, The Alaska Sea Grant College Program, under the direction of the United States National Oceanic and Atmospheric Administration (NOAA), Office of the Chief Scientist, published a *Report of the Interagency Task Force on Persistent Marine Debris* in 1988. Selected fishery-related recommendations and conclusions from these meetings are presented in Appendix 1.

Despite the passage of over 16 years since the first workshop, the recommendations and conclusions of subsequent meetings with regard to monitoring and removal (mitigation) of marine debris are notably consistent. Certainly, in part, this speaks to the wisdom of early conference and task force participants in identifying seminal conclusions and recommendations that have remained relevant. Equally as certain, the persistence of recommendations and conclusions over time reveals both the need for continued monitoring, and increased mitigation, of this persistent problem. Following are synopses of the four most frequently cited recommendations and conclusions from previous meetings with specific regard to environmental monitoring and marine debris removal:

1) Identify the distribution, abundance, density and type of persistent debris in the marine environment.

The first Workshop on the Fate and Impact of Marine Debris (Shomura and Yoshida 1985) affirmed the widespread occurrence of debris of terrestrial and aquatic (shipborne) origins in the marine environment and concluded that research on marine debris distribution was needed. Subsequent conferences reiterated the need for research to enhance understanding of marine debris dynamics in the world's oceans to facilitate mitigation efforts (Shomura and Godfrey 1990, Alverson and June 1988, Coe and Rogers 1997, Faris and Hart 1995). Specifically, information on distribution, abundance, density and macro- and meso-scale movements of marine debris were deemed incomplete. Also noted was the paucity of information on marine debris in oceanic regions other than the North Pacific (Shomura and Yoshida 1985, Alverson and June 1988).

2) Determine the fate of persistent debris in the marine environment.

Where marine debris is present, it poses variable risks depending on its persistence in the marine or littoral environment. Further, the susceptibility, or lack thereof, of plastic debris to nonchemical deterioration and chemical degredation (bio-, photo-, thermooxidative and hydrolytic; see Andrady 1990) affects its potential for environmental damage such as ghost fishing, entanglement and ingestion by wildlife and substrate damage. Recommendations for research pertaining to the fate of marine debris were presented at the1984 Workshop on the Fate and Impact of Marine Debris (Shomura and Yoshida 1985) and reiterated in1994 at the Third International Conference on Marine Debris (Coe and Rogers 1997, Faris and Hart 1995).

3) Recover (clean) marine debris from the marine and littoral environment.

Once in the marine environment, the recovery of debris is the most straightforward mechanism to mitigate environmental damage. The North Pacific Rim Fishermen's Conference on Marine Debris advocated an examination of cost effective systems to facilitate the recovery and return of lost fishing gear (Alverson and June 1988). The Interagency Task Force on Persistent Marine Debris recommended that US NOAA collaborate with fishermen and equipment manufacturers to develop pragmatic ways to improve recovery of lost fishing gear (Alaska Sea Grant 1988). Recovery of lost gear, through incentives or other means, and the evaluation of the effectiveness of efforts to clean up ghost nets were included in recommendations of the Third International Conference on Marine Debris (Coe and Rogers 1997, Faris and Hart 1995).

4) Conduct research on environmental impacts of marine debris.

Efforts to establish, and continue, examinations of the effects of marine debris on the environment have been repeatedly recommended. Early recommendations sought to document evidence of wildlife interactions with debris (Shomura and Yoshida 1985). Subsequent conclusions advocated increased support of studies of entanglement of wildlife in marine debris, particularly threatened, endangered or depleted species (Alaska Sea Grant 1988, Shomura and Godfrey 1990). Also noted was the need to investigate impacts of persistent debris ingestion on such organisms as seabirds, marine turtles and marine mammals (Shomura and Godfrey 1990, Coe and Rogers 1997, Faris and Hart 1995). The Third International Conference on Marine Debris included discussion on the potential for the introduction of alien species by marine debris and recommended investigations addressing this concern (Coe and Rogers 1997, Faris and Hart 1995).

Derelict Fishing Gear Monitoring and Removal Actions

Beach Surveys

The first systematic assessments of derelict fishing gear resulted from beach surveys, which continue to provide valuable information on the prevalence of derelict fishing gear (see Ribic *et al*. 1992). These studies are often a more cost effective way of monitoring debris trends than at-sea efforts, and may be completed concurrently with environmental monitoring of wildlife populations (Torres *et al.* 1997, Hucke-Gaete *et al*. 1997, Henderson, in review). Ribic and Johnson (1990) classify beach surveys as either beach-focused or ocean-focused. Beach-focused surveys estimate the amount of debris on a specific beach at a specific time. Ocean-focused surveys examine trends in marine debris on specific beaches over time as an indicator of oceanic conditions. Ocean-focused surveys have provided important information on large or very large derelict fishing gear (nets and rope) trends. If derelict fishing gear is removed from beaches during these studies, mitigation of further environmental damage, such as wildlife entanglement, is possible.

An opportunistic study on Alaska's Amchitka Island was begun in 1972 by Theodore Merrell of the US National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS). The majority of anthropogenic debris on Amchitka Island was composed of derelict fishing gear components (Merrill 1985). Over time, the focus of this project evolved from the amount and type of debris present to the use of trawl web dynamics to assess the impacts of MARPOL Annex V (for a more detailed chronology of this study see Ribic *et al*. 1992). Derelict fishing gear on these beaches was routinely removed in later years of the study (Ribic *et al*. 1992).

Beach surveys of derelict fishing gear on the remote Northwestern Hawaiian Islands (NWHI) from 1982 to 1986 documented the presence of 773 net or net fragments and were completed in conjunction with studies on entanglement rates of the endangered Hawaiian monk seal (Henderson, unpublished data). Recently, Henderson (in review) reported no decline in the amount of derelict fishing gear on the NWHI from 1982 to 1999, suggesting a failure of MARPOL Annex V to reduce the impacts of derelict fishing gear in this region. Until the late 1990s, derelict fishing gear was regularly burned on the beaches of these atolls to reduce the entanglement hazard to monk seals and other wildlife. Subsequently, due to concern over toxic byproducts, burning of debris was restricted in areas under the jurisdiction of the U.S Fish and Wildlife Service, tasked with management of the Pacific Remote Island National Wildlife Refuges. Presently, derelict fishing gear that accumulates on these islands is analyzed and stored in bins and later removed to ships by a multi-agency partnership led by the US NMFS. In 1999 alone, 12,500 pounds of derelict fishing gear were removed from the beaches of just two NWHI (Donohue, unpublished data).

Slip and Burton (1991) examined the beaches of two islands in the Southern Ocean, Heard Island and Macquarie Island. Heard Island, in the Indian Ocean sector, is near fisheries supported by the Kerguelen Plateau (Williams 1988). Macquarie Island is in the Australasian sector, which does not support a regional fishery. Fishery related debris accounted for 40% of all artifacts at Heard Island and 29% on Macquarie Island.

Beach surveys for marine debris have also been conducted in other regions, most often coupled with cleanup efforts. These beach cleanups have been conducted in the USA, the UK and Australia, often relying on volunteers and conducted near metropolitan centers (Jones 1994, Ribic *et al.* 1996 and Rees and Pond 1995). For example, in Australia, fishing debris accounts for 2-41% of the total debris on beaches (Slater 1991, Edwards *et al*. 1992, O'Callaghan 1993 and see Jones' 1994 review). Derelict fishing gear is also a notable component of beach surveys for marine debris in Puerto Rico, Mexico and Barbados (Coe *et al*. 1996).

Concerns associated with beach surveys include logistical limits to geographical areas surveyed or cleaned, potential inherent biases associated with differential fates of marine debris types at sea (Dixon and Dixon 1981a) and inconsistent or statistically weak sampling designs which prevent meaningful comparisons between efforts. Nevertheless, beach surveys for derelict fishing gear provide valuable information, particularly where a time series of data exist, and provide a mechanism for large numbers of the public to involve themselves in marine management issues. Lastly, volunteer beach cleanups are the primary mechanism for the removal of marine debris from the littoral environment.

Shipboard Sighting Surveys

Shipboard sighting surveys for the assessment of marine debris distribution and amount consist of visually inspecting the ocean surface for floating debris. This method is particularly suited for medium to large derelict fishing gear items (see Ribic *et al*. 1992 and Hess *et al.* 1999), and requires dedicated or opportunistic sea craft, good visibility and favorable weather. Observers stationed on the flying bridge or other elevated sections of the ship visually search for debris items in strip or line transects. During strip transects, debris items are counted on the side of a ship within a specified distance, commonly ranging from 50 m (Day and Shaw 1987, Day *et al*. 1990a) to 100 m (Dixon and Dixon 1983). During line transects all debris items visible are counted regardless of their distance from the ship. When the perpendicular distance of the objects to the ship can be accurately measured, the line transect method is preferable (Ribic 1990, Burnham *et al.* 1985). Platforms of opportunity are often used as a result of cost constraints and thus the sampling area, the height of the observer above the water, ship speed, etc. may not be controlled by the researcher. These factors affect the accuracy of the assessments (Mio and Takehama 1988, Ribic *et al.* 1992). Furthermore, as the characteristics of the debris (size, color, buoyancy, shape) affect its visibility to surveyors, accurate characterization of debris is not readily accomplished (Mio and Takehama, 1988).

Despite these challenges, numerous informative sighting surveys have been completed. Dedicated vessels combined with vessels of opportunity have been used in Pacific-wide surveys conducted by the Fisheries Agency of Japan from 1986 to 1991 (Matsumura and Nasu, 1997). Matsumura and Nasu (1997) reported derelict fishing net density to be relatively higher in the midlatitudinal area of 20º to 30º N, 150º to 130º W of the eastern Pacific Ocean. They also noted a high density of derelict fishing nets on the Pacific Ocean side of Japan from 30º to 40º N, 140º to 150º E. The distribution of derelict fishing gear other than nets was found to have a wider general distribution, with the greatest densities (greater than 120 pieces per 100 square nautical miles) found from 25º to 35º N, 130º to 180º W. Mio *et al*. (1990) and Mio and Takehama (1988) previously reported a high-density area of derelict fishing nets northeast of Hawaii during sighting surveys conducted in 1986. Day and Shaw (1987) also completed a multiple year study in the Gulf of Alaska in 1984 and 1985. Other baseline studies have been conducted in the North Pacific (Dahlberg and Day 1985, Ignell 1985, Jones and Ferrero 1985, Ignell and Dahlberg 1986, Day et al. 1990 and Shaw 1990). Additional regional sighting surveys were conducted around the Pribilof Islands in the Bering Sea, the main breeding islands of the northern fur seal (*Callorhinus ursinus*) (Yoshida and Baba, 1985, Baba *et al.* 1988, 1990). Fewer sighting surveys for marine debris have been completed in oceans other than the Pacific; however, the North Sea and Mediterranean Sea have been surveyed using vessels of opportunity (Dixon and Dixon 1983 and Morris 1980, respectively). Removal of derelict fishing gear is not a customary component of sighting surveys.

Shipboard Trawl Surveys

Shipboard trawl surveys can be used to survey marine debris on the surface of the water or on the seafloor. Neuston-type nets can be used to sample small floating marine debris and larger nets can be deployed to sample debris that has sunk to the benthos (Ribic *et al.* 1992). The latter are useful for the assessment of medium to large derelict fishing gear items. Trawling techniques mimic those used for fishing, with the net deployed to sample or "catch" debris resting on the seabed (see Ribic *et al*. 1992). The mesh size of the net used determines the minimum size of debris that may be caught. Thus, when comparing trawl-sampling studies, mesh size must be accounted for in the interpretation of results. Other factors that may affect trawl-sampling studies include vessel variability, weather, footrope variability, depth variability and measurement variability (Ribic *et al.* 1992).

Trawl sampling studies may be conducted opportunistically in association with commercial, experimental or managed fisheries or with dedicated cruises targeting marine debris. The common occurrence of marine debris in benthic trawls on the continental shelf of the Northeast Gulf of Alaska was reported as early as 1976 (Jewett 1976). Bering Sea fishing areas were also found to have greater amounts of benthic debris than areas not fished (Feder *et al.* 1978). More recently, working with the Alaska Department of Fish and Game, Hess *et al.* (1999) investigated fishery-related items caught during benthic trawls to survey crab and groundfish resources around Kodiak Island, Alaska. In the three years of their study, fishery-related items comprised 46%, 42% and 38% of the total benthic debris recovered. Fishery-related debris densities ranged from 4.5-25.0 items/km^2. After evaluation of fishery effort near Kodiak Island, and the subsample of fishery-related debris deemed potentially harmful to wildlife by the investigators, Hess *et al.* (1999) concluded that annual benthic trawl surveys for debris around Kodiak Island were unwarranted. The debris densities reported by Hess *et al.* (1999) were less than those reported for other benthic trawl surveys in the Bay of Biscay (203 items/km^2; Galgani *et al.* 1995a) and on the continental shelf of the Western Mediterranean Sea (1935 items/km^2; Galgani *et al*. 1995b) and were between those reported by June (1990) for the Eastern Bering Sea (2-7.5 items/km^2) and off the Oregon Coast (150 items/km^2).

Although shipboard trawl surveys have been used most extensively for surveying benthic marine debris, they cannot be employed in very shallow waters, on steep slopes or in sea canyons. A result of the shipboard trawl survey technique is the removal of sampled derelict fishing gear from the environment. Shipboard trawls have not been used in dedicated cleanup efforts.

Benthic Diving Surveys

Other methods investigated or proposed to survey benthic marine debris involve submersibles, towed camera systems and divers. The latter is the main focus of this section, as diving survey and removal efforts have recently been particularly successful for removing large amounts of derelict fishing gear from coral reef environments of the NWHI (Donohue, unpublished data). The cost and availability of manned submersibles and remotely operated vehicles (ROVs) have limited their use in marine debris surveys (Ribic et al. 1992). A manned submersible equipped with an external-mounted video camera was used by Carr *et al*. (1985) to survey commercial gillnetting sites in 1984. Carr *et al*. (1985) surveyed over 40.5 ha and documented 10 derelict gill nets. Galgani and Andral (1998) investigated the use of a towed camera array to survey benthic marine debris, but the inability to quantify small debris items and difficulties with the deployment and positioning of the array prevented its successful use.

Diving surveys for benthic marine debris have not been widely conducted, but have recently been utilized extensively in the NWHI. Carr *et al*. (1985) used scuba divers to monitor the ghost-fishing of a simulated derelict gill net set in Cape Cod Bay. Benthic debris in McMurdo Sound, Antarctica, was also documented with divers (Lenihan et al. 1990).

A large-scale project utilizing divers to conduct surveys for, and remove, derelict fishing gear in the NHWI began with a pilot study in 1996 (Boland, unpublished data). The US NMFS Honolulu Laboratory identified marine debris of a maritime origin, particularly derelict fishing gear, as a threat to the coral reef ecosystems of the NWHI (Brainard *et al*. 2000, Henderson in review). In 1996 and 1997, the US NMFS Honolulu Laboratory refined diver survey and removal techniques, removing 10,000 pounds of derelict fishing gear from the shallow coral reefs of the NWHI (Boland, unpublished data). In 1998 and 1999, the US NMFS Honolulu Laboratory expanded efforts by partnering with a consortium of state, federal and private organizations. Presently, the US NMFS leads annual multi-agency, multiple ship efforts to survey and remove derelict fishing gear from the NWHI. The distribution, density, type and organic fouling of derelict fishing gear is documented using snorkel divers towed in systematic parallel track survey transects behind small boats. Debris is documented using a global positioning system (GPS) and still and video photography. Derelict fishing gear is subsequently recovered using small boats and snorkel and scuba divers supported by US NOAA and US Coast Guard vessels. In 1999 alone, 18,500 pounds of derelict fishing gear was recovered from the NWHI coral reefs (Donohue, unpublished data). To date, over 77,000 pounds of derelict fishing gear have been recovered from the NWHI by these efforts (Boland, unpublished data, Donohue, unpublished data). Coral reef debris density ranged from 1.0 to 62.2 items/km^2 (Donohue, unpublished data).

Human divers can execute surveys for derelict fishing gear in areas too shallow to employ submersibles or ROVs, and where seabed topography restricts trawl surveys (Ribic *et al*. 1992). Furthermore, human divers can remove derelict fishing gear from the substrate in a surgical fashion, reducing additional environmental damage to reefs during removal. Small sea craft towing divers can be deployed from ship platforms at oceanic sites or from land-based laboratories for coastal surveys. Diving surveys are most easily executed in benign climates and relatively shallow waters where diver safety can be maximized.

Drawbacks associated with the use of divers to survey and remove marine debris include expense, logistics, reliance on favorable weather, and good water visibility. Although supported through in-kind contributions, the 30-day multi-agency derelict fishing gear survey and removal effort in the NWHI in 1999 cost in excess of one million US dollars. These costs include two large ship platforms for housing and deploying divers and small boats, transport of recovered debris back to Honolulu, Hawaii. Once derelict fishing gear is recovered it must be disposed of properly at port either through landfill, incineration or recycling. Additionally, in ecologically sensitive areas where endangered or protected species occur, studies must be planned so as to minimize impacts to wildlife.

Remote-Sensing/Oceanography

Recently, the utility of remote sensing to monitor and assess marine debris has been investigated. Over the past two years, the US NOAA Fisheries and NOAA CoastWatch oceanographers have been developing methods to apply knowledge of oceanographic processes and use of satellite remote sensing of ocean surface properties to identify and monitor regions where derelict fishing gear and other forms of marine debris would most likely accumulate (see Brainard *et al.* 2000).

Using an array of satellite environmental sensors, oceanographers are now able to observe properties of the ocean surface with much improved spatial and temporal resolution. These properties include surface winds (QuikSCAT and other scatterometers), sea surface temperature (AVHRR and GOES), sea surface height and computed geostrophic currents (TOPEX/Poseidon) and ocean color or chlorophyll (SeaWiFS and earlier CZCS). With these modern tools, scientists are now better prepared to assess the extent of the threat posed by marine debris over the vastness of the global ocean.

Using high-resolution scatterometer winds to compute wind stress curl over the Pacific Ocean, Brainard *et al.* (2000) have confirmed and expanded upon Kubota's (1994) finding of a marine debris accumulation region centered north of the Hawaiian Islands. Regions of oceanic convergence are most likely to accumulate marine debris while regions of oceanic divergence are least likely to accumulate marine debris. Brainard *et al*. (2000) found oceanic convergence to be highly nonstationary with pronounced seasonal and interannual variability. Convergence in the North Pacific is highest along the subtropical front in the western half of the basin during the winter months. In the vicinity of the NWHI, and in the main Hawaiian Islands, accumulation would be expected to be highest to the northwest and lowest to the southeast. During the summer, convergence is generally much weaker and more diffuse across the North Pacific with the region of highest convergence shifted to the eastern portion of the ocean basin several hundred miles off the California and Oregon coasts. The region of high convergence, or likely accumulation of marine debris, is strengthened and enlarged during periods identified as El Niño warm events in the tropical Pacific. During the 1992 and 1998 El Niño events, the region of convergence was observed to expand much further south to include the main Hawaiian Islands. This result partially explains the documented increase of marine debris found on beaches and reefs of the main Hawaiian Islands during 1998 (Brainard and Foley, unpublished data).

Presently, oceanographic knowledge and satellite observations of ocean conditions are being used to assist marine debris removal efforts by helping to locate areas in the NWHI and elsewhere that are most likely to have the highest concentrations of marine debris. From an oceanographic viewpoint, the coral reef ecosystems at Kure, Midway, and Pearl and Hermes Atolls are expected to have the highest average encounter rate of marine debris since these areas are more centrally located in the strongest mean convergence zone. Of course, bathymetry, reef structure and local processes such as small-scale flow regimes and wave forcing, also play a significant role in entangling debris on coral reefs and beaches.

These oceanographic analyses suggest that much lower accumulation rates of derelict fishing gear and other marine debris would be expected at most of the other tropical islands and atolls of the Pacific. Exceptions include the Japanese islands of the Ogasawara Archipelago, Kazan Group and Minami-Tori, where moderately high accumulation rates might be expected. The same analysis predicted very low accumulation of marine debris in the US Line and Phoenix Islands of the central equatorial Pacific; this was verified during a coral reef assessment cruise to these islands in March 2000 (Brainard, unpublished data). A similar analysis is currently underway for the entire Pacific basin (Brainard, unpublished data). Preliminary results indicate that wind-driven ocean convergence is less intense in the South Pacific Ocean. However, there are broad regions of moderate ocean convergence, which may play a significant role in the transport and accumulation of marine debris. The utility of oceanographic analyses in other oceans to direct marine debris removal efforts should be investigated.

The removal of derelict fishing gear at sea, before it encounters reefs or damages wildlife, may be the most advantageous mitigation action once debris enters the marine environment. An ambitious proposal by the NMFS Honolulu Laboratory aims to investigate the feasibility of such efforts. Once the majority of the derelict fishing gear is removed from the coral reefs and beaches of the NWHI, Honolulu Laboratory scientists are proposing a comprehensive multi-agency program to begin removing marine debris at sea. By so doing, they hope to prevent much of the ecological damage, which is now threatening the coral reef ecosystems and protected species of the region. This plan takes advantage of the fact that ocean currents and convergence processes do an efficient job of accumulating marine debris from around the Pacific Ocean into relatively well-defined zones. Combining satellite observations of winds, sea surface temperatures (SST), ocean color and sea surface height, they believe they can identify general regions to direct aircraft and ships to interdict debris at sea. These regions of highest convergence would be along frontal zones of the order 100 km by 1000 km. These scales are well covered by satellite-based measurements. However, the oceanographic tools (e.g., SST, ocean color and wind) are useful only for inferring likely positions; they do not have sufficient resolution to image the actual debris. Using aircraft equipped with synthetic aperture radar (SAR) or hyper-spectral visible light sensors, scientists could resolve scales less than 1 meter, allowing them to map individual pieces of derelict fishing gear on the ocean surface (see below). This information would then be transmitted to surface debris removal vessels. Provided with maps of areas of highest concentration, the vessels could then use helicopters to guide them to individual derelict fishing gear items for at-sea removal. Although this multi-level scenario presently seems fanciful and costly, at-sea removal would potentially be no more expensive per ton of debris removed than the existing methodology of using divers to locate and cut away debris from the coral habitat.

Remote-Sensing/Geographic Information Systems (GIS)

Although significant efforts to find and remove derelict fishing gear have been ongoing for a number of years, particularly in the NWHI, traditional beach cleanups and ship-supported recovery efforts are limited to relatively small areas. For example, less than 5% by area of the NWHI reef habitat has been surveyed and even less of the habitat has been cleared of debris. To facilitate efforts to identify and remove derelict fishing nets from the NWHI management area, the NMFS Honolulu Laboratory has begun to investigate the use of remotely sensed imagery from a variety of sources linked with a broad range of other data (ocean winds and shear lines, field surveys, bathymetry, political boundaries) within a geographic information system (GIS). Remote imagery combined with in-situ survey data will be used to map and assess marine debris and to inform and improve debris removal efforts planned in 2000 and 2001. Although remote sensing has proved useful in a wide array of marine environmental applications, the ability to use imagery from a variety of airborne and satellite sensors to locate and identify derelict nets and other marine debris is unproved. Until recently, remote-sensing applications have been hampered by inaccurate base maps and low-resolution imagery available from US government mapping agencies and satellite sensors. Full utilization of the GIS has been limited by the lack of accurate geographic data and limited amounts of marine debris survey data collected.

In 2000, a number of proposals to obtain high-resolution imagery from three separate sources have been submitted by NMFS Honolulu Laboratory and tentatively approved. As part of the Hawaii Coral Reef Initiative, funding has been promised (1) to obtain high resolution IKONOS satellite images of some of the NWHI that can be used to create valid base maps and assist in the identification and removal of marine debris, derelict nets particularly, that threaten the health of NWHI coral reef ecosystems, (2) to identify alien species that may be introduced to those ecosystems on such nets, and (3) to begin to develop a GIS-based remote sensing capability to monitor and model changes to shallow-water (<20 m) coral reef habitat in the NWHI. The privately owned and operated IKONOS imager satellite can provide 1-meter resolution panchromatic and 4-meter resolution multispectral (red, green, blue bands) imagery at 12-meter horizontal and 10-meter vertical accuracy with no ground control. With ground control stations, an exceptional 2-meter horizontal and 3-meter vertical accuracy can be attained. The IKONOS instrument can be tasked to provide complete coverage of the area, and if it can be used to identify derelict nets, will allow resources currently devoted to finding the nets to be dedicated to removing nets. Combined with other imagery and modeling efforts that have been successful in identifying wind convergence zones that influence the movement and accumulation of derelict nets (see previous section), the IKONOS imagery should be useful for identifying nets that are entangled on shallow reefs. At the resolution available with the IKONOS imagery, nets of ~2 m diameter should be identifiable if fieldwork is able to provide the necessary classification parameters. At minimum, this high-resolution imagery will be used to create accurate base maps of the land and emergent and shallow water (<20 m) reef areas of the NWHI. The major constraint on the use of IKONOS imagery is cost. Funding available this year will enable the acquisition of only 3 of the 10 major reef areas of the NWHI. Through a series of cooperative arrangements with other government agencies, IKONOS imagery of other areas may become available in 2001.

A second NMFS Honolulu Laboratory proposal that was recently approved involves the use of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery. ASTER is an imaging instrument that is flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER is the only high spatial resolution instrument on the Terra platform. Although the resolution from ASTER imagery may be too coarse to detect derelict nets, high-resolution IKONOS images could be used to develop a spectral library for derelict nets and this library used to determine if reflectance signatures of nets can be identified in the ASTER imagery. ASTER imagery will also be used to improve base maps, categorize and map shallow-water bottom types and perhaps map and monitor coral reefs. One major advantage of the ASTER imagery is that it will be obtained for no charge and will provide summer and winter imagery for the next five years of the entire NWHI chain, as well as the other US possessions in the Pacific.

A final source of imagery may be the AVIRIS (Airborne Visible InfraRed Imaging Spectrometer) imager. AVIRIS is a unique optical sensor that flies aboard a NASA ER-2 airplane at approximately 20 km above sea level, providing a ground resolution of 20 meters. The main advantage of AVIRIS is that it is a true hyperspectral instrument that allows very precise spectral segregation, to possibly identify the reflectance or equivalent signatures of derelict fishing nets. The disadvantages include the relatively coarse resolution and the cost of the imagery for those other than co-principal investigators. Data from a series of flights over the NWHI in Spring 2000 may become available to NMFS researchers from the principal investigators.

Remote-sensing methods may prove effective at identifying and mapping derelict net accumulations. The success of the methods will depend on the ability to correctly classify the unique spectral signatures of the nets and to be able to distinguish the nets from their surroundings. Since proper classification depends on verification through in-situ fieldwork, precise field mapping is a key component to the success or failure of such initiatives.

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Appendix 1. Fishery related recommendations and conclusions from previous marine debris conferences.

Workshop on the Fate and Impact of Marine Debris, 1984; Honolulu, Hawaii (Shomura and Yoshida 1985)

Conclusions and Recommendations

Studies should be undertaken to:

1. Determine the sources and distribution of debris, possibly through development of a sampling methodology.

2. Determine the fate of lost gear and debris once it is deposited in the marine environment.

3. Develop a means of identifying derelict gear through creation of a reference collection.

4. Obtain worldwide data on vessel disablement as a result of interactions with marine debris.

Additional efforts should be undertaken to:

1. Obtain data on gear problem in areas other than the North Pacific

2. Expand existing stranding networks for marine mammals, birds, and turtles, and incorporate examinations for evidence of interactions with debris.

North Pacific Rim Fishermen's Conference on Marine Debris, 1987; Kailua-Kona, Hawaii (Alverson and June 1988)

Identified research needs as follows:

1. Expansion of national and international studies of the density, distribution, and movement of marine debris in the world's oceans.

2. Examination of cost-effective systems to facilitate the identification, recovery, and return of lost fishing gear to port or owners.

3. Continuation and expansion of beach surveys to monitor trends in marine debris abundance and type. This is particularly important in the North Pacific, but warrants consideration in other ocean regions.

Report of the Interagency Task Force on Persistent Marine Debris, 1988: Booklet produced and published by the Alaska Sea Grant College Program under the direction of the NOAA, Office of the Chief Scientist (Alaska Sea Grant 1988)

1. Federal agencies should continue to participate actively in international forums to reduce persistent marine debris.

2. The administration should support the NOAA Marine Entanglement Research Program by including it in the administration's fiscal year 1990 budget and for at least five years thereafter.

3. The topic of persistent marine debris should be included in the five-year Federal Plan for Ocean Pollution Research, Development, and Monitoring.

4. NOAA, the US Fish and Wildlife Service, the Marine Mammal Commission and other agencies should expand research and monitoring activities to determine more precisely impacts of persistent marine debris on fish and wildlife populations, particularly endangered, threatened, and depleted species.

5. EPA, NOAA, US Coast Guard, and other agencies should carry out research to determine contributions of land-based and vessel sources of plastic refuse to the overall problem, as well as ways to reduce plastic debris from all sources.

6. NOAA should work with fishermen and equipment manufacturers to develop pragmatic ways to improve ways to recover lost fishing traps and nets

7. Beach Clean-up and Monitoring: Federal agencies should work cooperatively among themselves, as well as with state agencies, private industry, and environmental groups to remove marine debris from beaches and other parts of the marine environment. Federal agencies should encourage coordination with state and local authorities for conducting systematic monitoring of marine debris accumulation and impacts in order to assess compliance with regulations prohibiting disposal of plastics and controlling other solid waste discharges into US waters.

8. Federal agencies that manage coastal properties should set up actions to remove persistent marine debris.

9. Federal agencies should support local volunteer beach clean-up efforts as well as the collection and interpretation of data on materials that the volunteers remove. Federal managers should encourage employees to participate in volunteer clean-ups.

Second International Conference on Marine Debris, 1989; Honolulu, Hawaii (Shomura and Godfrey 1990)

General conclusion: "The recommendations from the 1984 FIMD workshop have not been fully met. Efforts to measure the sources and amounts of persistent debris have been greater in the North Pacific than in any other ocean area, but a full understanding of the dynamics of input, output, and circulation remains well in the future."

Recommendations:

1. Development of a set of standard methods for surveys of the amounts, types, and sources of marine debris.

2. Establishment of an international committee or organization to further collaborative research on the impacts of entanglement on living marine resources.

3. Design and implementation of baseline experiments to establish the lethal and sub-lethal impacts of persistent debris ingestion by sea turtles and seabirds.

4. Design and implementation of experiments to evaluate ghost fishing in gillnet and trap fisheries with high gear loss rates, developing mitigative measures as needed; and

Third International Conference on Marine Debris, 1994; Miami, Florida (Faris and Hart 1995, Coe and Rogers 1997)

1. Focus on and publicize the problem of combined sewer overflows. Continue research on terrestrial sources of debris.

2. Rigorously investigate the sub lethal impacts of debris ingestion among turtles and birds - how it creates a false sense of satiation, dilutes nutrients, impairs digestion and affects reproductive capacity.

3. Research and implement mechanisms to reduce fishing gear loss. These could include technological changes in gear design or incentives to recover lost gear. Given the appropriate incentives, the collection of derelict gear may be feasible.

4. Investigate the fate of plastic and other debris after they break down into minute particles in the marine and littoral environment. Research their potential impact on marine organisms.

5. Investigate the scope and importance of organism transfers by marine debris, especially the introduction of invasive alien species that could disrupt native communities and ecosystem functions.

6. Investigate the amounts, accumulation rates and impacts of debris on the seafloor and the potential for large-scale impacts by smothering.

7. Monitor rates of entanglement and ingestion among selected species at specific sites. Collaborate with existing studies in certain regions. For instance, records of entanglement and ingestion in the Antarctic Treaty region are collated by the CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources) Scheme of International Scientific Observation. Flagship species such as marine turtles and cetaceans can be used to promote field observations.

8. Establish an impact reporting system to promote and collate observations by beach users, fishermen, oceanographers, scuba divers and others. Start by compiling past records.

9. Make efforts to recover lost fishing gear in areas where it is likely to be concentrated. Also, take steps to better evaluate the kinds and amounts of fish caught and the potential effectiveness of such work to clean up hazardous ghost fishing gear. Establish a system to record gear loss by commercial fishermen.